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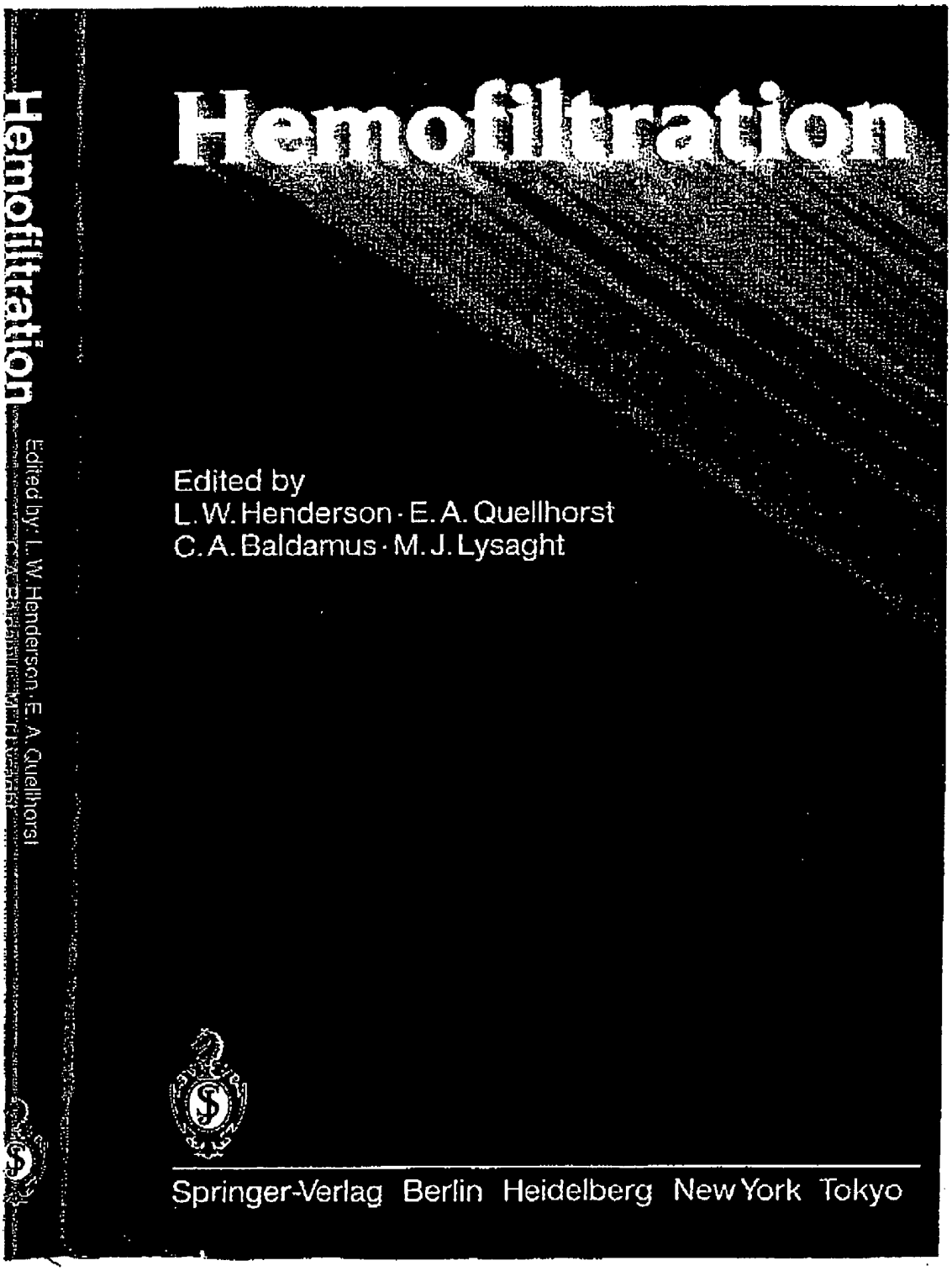


Use of weight scales in ~~hemodialysis~~ hemofiltration has been done since at least 1976

# Equipment for Hemofiltration

B. VON ALBERTINI

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## Introduction

For hemofiltration to be a practical alternative to routine hemodialysis, it must be delivered by fail-safe automated equipment, which provides the essential functions of the treatment and, at any time, maintains the patient's safety without the necessity of human intervention. A variety of hemofiltration machines are available which perform this task reliably and accurately.

Hemofiltration lowers the concentration of uremic solutes in the patients with end-stage renal disease by the periodic removal of a large fraction of total body water and its solutes by ultrafiltration and the simultaneous replacement with a physiologic solution. For this purpose, the patient's blood circulates during the treatment through an extracorporeal circuit where an ultrafiltrate of plasma is removed in a hemofilter and the blood volume is simultaneously reconstituted with replacement fluid. The total volume of exchange ranges from 20–40 liters per treatment, which is typically carried out in 4–5 h three times weekly.

## Operational Features

The equipment for hemofiltration has to meet three basic operational requirements:

a) it must safely accomodare the extracorporeal blood circuit,
b) it must provide the pressure for ultrafiltration in the hemofilter, and
c) blood volume must be accurately reconstituted by delivering substitution fluid.

While different technical approaches have been made to meet these requirements, all hemofiltration machines in use have these features in common:

### Extracorporeal Blood Circuit

Analogous to hemodialysis, blood gained from the patient's vascular access is pumped to the hemofilter and returned to the patient through a disposable plastic tubing set. Ultrafiltration is achieved in the hemofilter by exerting a hydrostatic pressure gradient across the membrane, resulting in the transfer of plasma water and solutes. Substitution fluid is delivered either proximally to the hemofilter (predilution) or into the venous drip chamber (postdilution).

The features of the equipment needed to operate the extracorporeal circuit are essentially identical to those of hemodialysis machines. During the treatment, 50–100 liters of heparinized blood are carried through the circuit by a peristaltic roller pump in the arterial line which, in conjunction with the resistance to flow, provides the driving force for the positive component of the transmembrane pressure gradient in the hemofilter. Safety features in the circuit include pressure monitors in the arterial and venous blood lines and an air detector linked to an automatic clamping device in the venous line. The machines are wired internally to shut off extracorporeal circulation whenever preset pressure values are exceeded or a line disruption occurs.

### Hydraulic Circuit

In contrast to the complex hydraulic components of hemodialysis machines necessary for the preparation of dialysate, this aspect of hemofiltration machines consists of two separate, comparatively simple circuits for ultrafiltrate and substitution fluid. A roller pump creates the negative component of the transmembrane pressure and carries the ultrafiltrate through a disposable tubing set from the hemofilter to a collection cannister. A negative pressure monitor in this circuit prevents preset transmembrane pressure limits from being exceeded, and a blood leak detector activates an alarm condition, which shuts off extracorporeal circulation, should a major membrane rupture occur.

In a separate circuit, substitution fluid is delivered from its containers into the blood line by another roller pump, which operates under the control of the balanc-

ing system. Other features of the circuit include a flow-through heater with thermostatic control and a thermometer for overheat alarm. The disposable sterile tubing set used in this circuit contains a segment for the heater and usually has multiple attachments for the collapsible plastic bags in which the fluid is purchased, thus permitting a completely sealed sterile circuit and preventing the accidental pumping of air into the blood circulation. Batch-prepared substitution fluid from a single open cannister has also been successfully used in recent years.

## Balancing System

The functionally most genuine part of the hemofiltration apparatus is the balance control, providing the matching of the volumes of substitution fluid and ultrafiltrate. Large volumes are exchanged in a short time during the treatment, and accurate control of fluid balance is of critical importance. Imbalance of ultrafiltration and substitution could rapidly lead to life-threatening volume depletion or overhydration of the patient. The pace of exchange is determined by the ultrafiltration rate obtained in the hemofilter. Since ultrafiltration rate changes during the treatment, it must be continuously monitored and the rate of fluid replacement adjusted accordingly. Moreover, the machine has to be programmable to remove the patient's weight gain between treatments by replacing the ultrafiltrate with a proportionally smaller volume of substitution fluid throughout the treatment.

# Solutions to Technical Problems

Early clinical investigators of hemofiltration had to rely on manual control of fluid balance while using components of hemodialysis machines for the extracorporeal blood circuit. Fluid balance was achieved with the help of bed scales and manual adjustment of the substitution pump, requiring constant supervision of the treatment. Most of the automated equipment available today originates from early prototypes developed in close association with key investigators. These developments occurred independently, and the various technical approaches in use reflect the different preferences and philosophies of these early investigators. A description of the various conceptual approaches can be found in some of the earliest publications on hemofiltration [1, 2].

Three different conceptual methods to achieve fluid balance in hemofiltration have been explored:

a) by volumetric control,
b) by gravimetric control, and
c) with control of flows.

## Volumetric Control

In this approach, fluid balance is achieved by measurement of volumes. Since both ultrafiltrate and substitution fluid are liquids, the displacement by volume of the ultrafiltrate is used to deliver an identical volume of substitution fluid to the patient. This concept is illustrated by the example of a single pump with two identical, separate tubing segments for ultrafiltrate and for substitution fluid, which ideally deliver identical volumes with each stroke. Similarly, volume control can be achieved by the alternate filling of a double cylinder with a single piston or a sealed chamber separated into two compartments by a flexible membrane. Such a system operates by means of the ultrafiltrate filling a previously empty compartment and displacing the separating piston or membrane, thereby forcing an identical volume of substitution fluid out of its previously full compartment.

While conceptually simple, accurate fluid balance by volumetric control in hemofiltration is difficult to achieve technically. Many of the technical problems result from the disparity of pressures in the two hydraulic circuits. Substitution fluid is delivered under positive pressure into the blood circuit, while ultrafiltrate is generated under negative pressure. The high ultrafiltration rates necessary to accomplish an adequate exchange within a reasonable time in hemofiltration cannot be obtained without exerting substantial negative pressures downstream of the membrane. As a result, dissolved air, which crosses the membrane with plasma water, forms gas bubbles which interfere with volumetric control of the ultrafiltrate. In order for such systems to operate accurately, the ultrafiltrate must be degassed in a separate step and the pressures within the control circuits carefully matched. Additionally, a set of valves is required to switch between alternate cycles for filling and emptying of the volume controller. Due to their technical complexity, volumetric hemofiltration systems have not found widespread acceptance. It is noteworthy, however, that the technical explorations of this approach in the past have substantially influenced the development of modern hemodialysis equipment. The newest generation of hemodialysis machines with volumetric ultrafiltration control is at least in part the result of efforts to develop such a system for hemofiltration.

## Gravimetric Control

Monitoring of fluid balance by weight instead of volume is the basis of this technique, which is used in the majority of available hemofiltration machines. Both ultrafiltrate and substitution fluid have similar specific weights, permitting effective control of the exchange with scales. Since the total volume of the ultrafiltrate and substitution fluid can be conveniently placed on the scale, accuracy of control is maintained throughout the treatment and is not influenced by differences in pressure and air bubbles. Technically, gravimetric control is achieved by either one single scale or two individual scales for ultrafiltrate and substitution fluid in combination with a microprocessor.

Single-scale systems operate by maintaining the weight of combined ultrafiltrate and substitution fluid constant throughout the treatment. At the onset, the container

for ultrafiltrate is empty and the one for substitution fluid full. Both are on the same scale and the combined weight is entered into an electronic or mechanical control as zero value. During the treatment, ultrafiltrate gradually fills is container. This is sensed by the scale as an increase in weight, which in turn activates a pump to remove substitution fluid from its container, deliver it to the patient, and thereby maintain the total weight on the scale constant. Desired weight loss during the treatment can be programmed either by diverting that volume of ultrafiltrate with a small preset pump from the circuit before reaching the scale or by mechanically diminishing the weight of the ultrafiltrate sensed by the scale. Both electronic and mechanical scales are used in gravimetric systems of this type and provide good accuracy of fluid balance.

A microprocessor operates hemofiltration machines with two independent electronic scales for ultrafiltrate and substitution fluid. The advantage of such equipment is that it is fully programmable and that the rates of ultrafiltration and substitution can be individually monitored throughout the treatment. The disadvantages relate to the complex electronics required and the need for costly electronic scales operating with sufficient accuracy within a wide weight range.

### Control by Flow

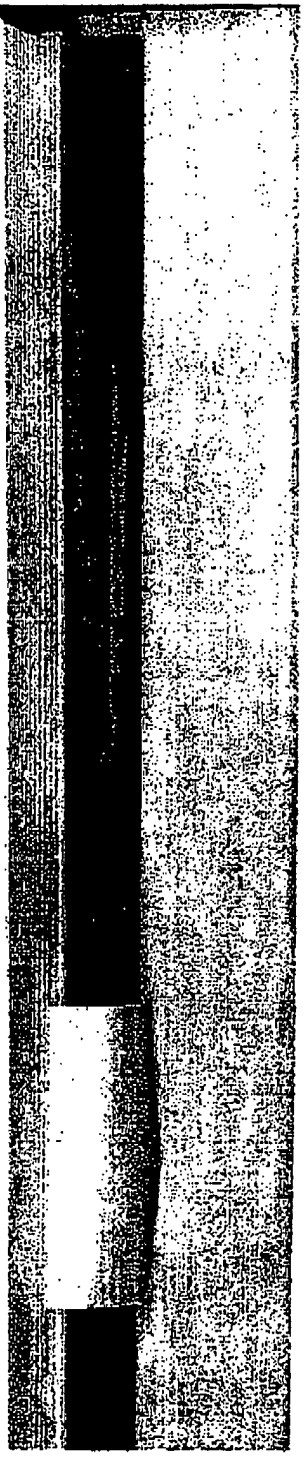
Fluid balance with this approach is achieved by monitoring the respective fluid flows in the ultrafiltrate and substitution circuits. Both flotation-type mechanical and electromagnetic flowmeters have been used experimentally for this purpose. For the same reasons as with volumetric systems, accurate, continuous control is difficult to achieve technically.

## Available Equipment

### Volumetric Systems

The first balance equipment for hemofiltration was developed for L. W. HENDERSON in 1973 at the University of Pennsylvania by G. KLIGER and E. HORN in association with D. CLEVELAND of Amicon [3]. Designed for the predilution mode, this system operated reliably with a reciprocating, paired piston pump matching the volumes of ultrafiltrate and substitution fluid. A float control in a separate reservoir under negative pressure prevented air from entering the volume controller with ultrafiltrate (Fig. 1).

An operational prototype for volumetric control of postdilution hemofiltration was developed around 1976 by E. STREICHER and H. SCHNEIDER in Stuttgart, West Germany [4]. Its key component is a small chamber divided by a flexible membrane into one compartment for ultrafiltrate and another one for substitution fluid. A set



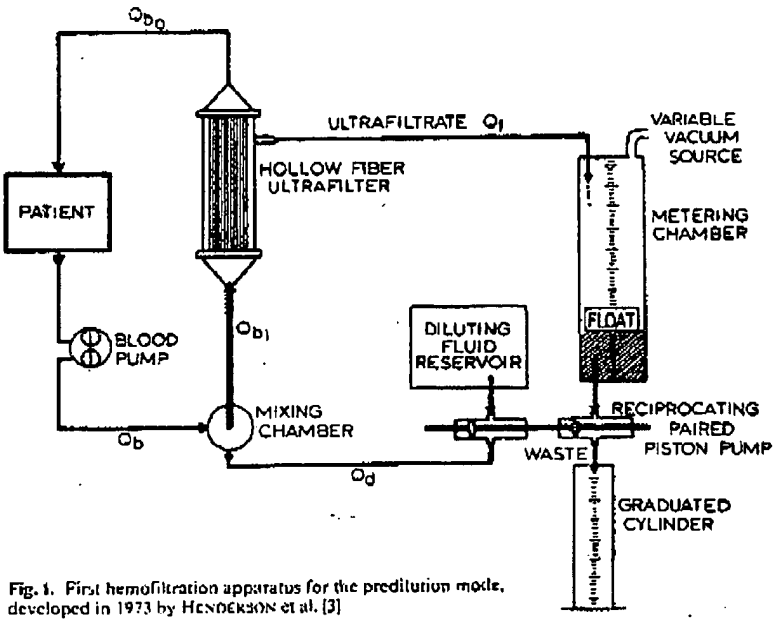



Fig. 1. First hemofiltration apparatus for the predilution mode, developed in 1973 by HENDERSON et al. [3]

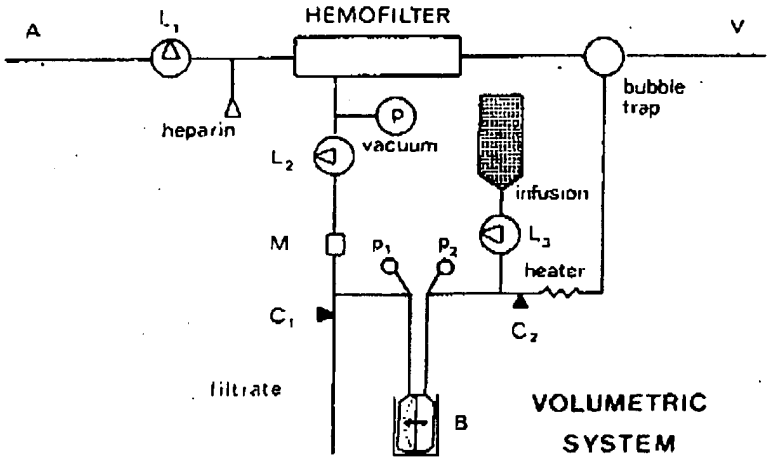



Fig. 2. Prototype for volumetric control of hemofiltration developed by STREICHER et al. [4]. A balancing chamber (*B*) is alternatively filled and emptied by the ultrafiltrate and substitution fluid. ($L_1$, $L_2$, $L_3$ pumps; $p$, $p_1$, $p_2$ pressure monitors; $C_1$, $C_2$ valve clamps; M, deaerator)

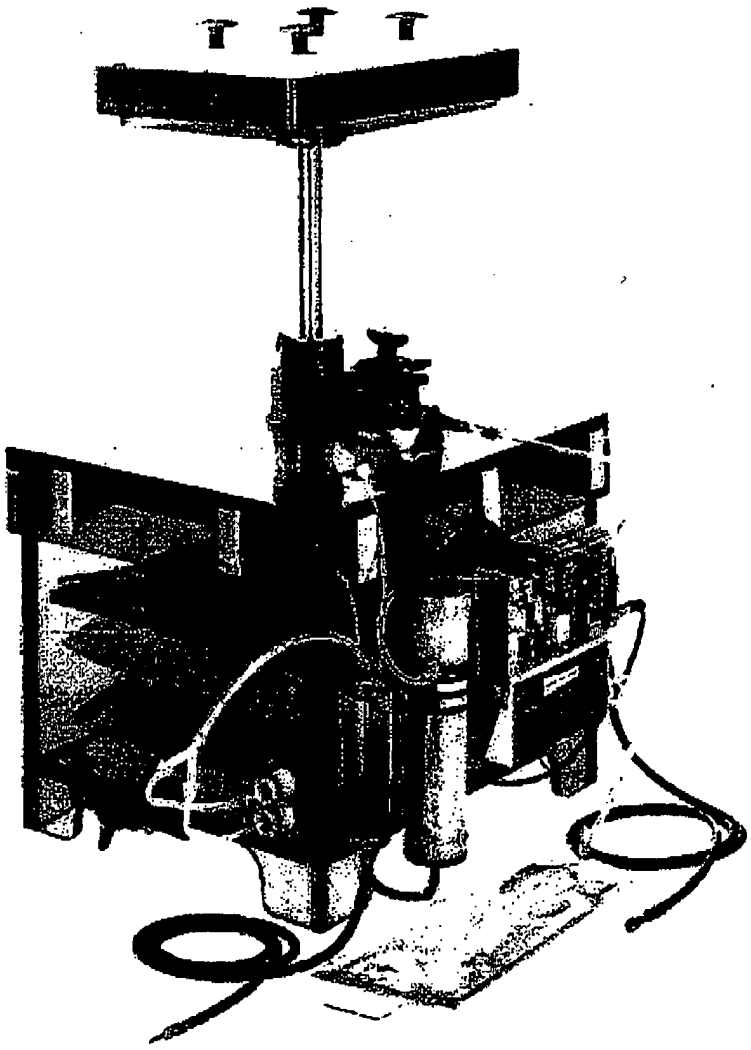


Fig. 3. Weight-driven volumetric balancing system for slow arteriovenous hemofiltration, developed by P. KRAMER and manufactured by Schi-Wa Arzneimittelwerk, Bad Liebenzell, West Germany

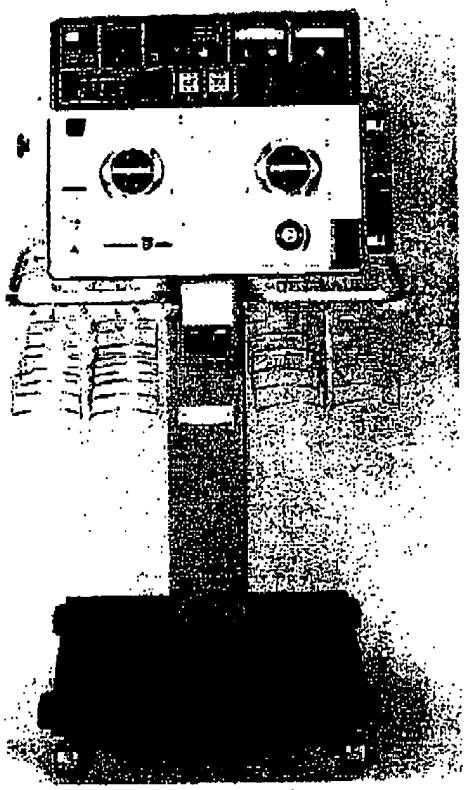


Fig. 4. Nipro NY-3 hemofiltration system (Nipro Medical Industries, Tokyo, Japan). Fluid balance is achieved by two matched pumps for ultrafiltrate and substitution fluid. The machine can hold 20 1-liter infusion bottles

of pressure-activated valves switches the system into two cycles, alternately filling and emptying the chamber with ultrafiltrate and thereby displacing simultaneously an identical volume of substitution fluid. To minimize the effect of freed air interfering with volume control, the system contains a degassing device in the ultrafiltrate circuit and operates under matched positive pressures (Fig. 2). Because of minor technical problems and lack of support, this project was later abandoned. This innovative approach, nevertheless, must be regarded as the forerunner of the newest generation of hemodialysis machines. Available only recently, these machines control ultrafiltration during dialysis by an essentially identical volumetric system.

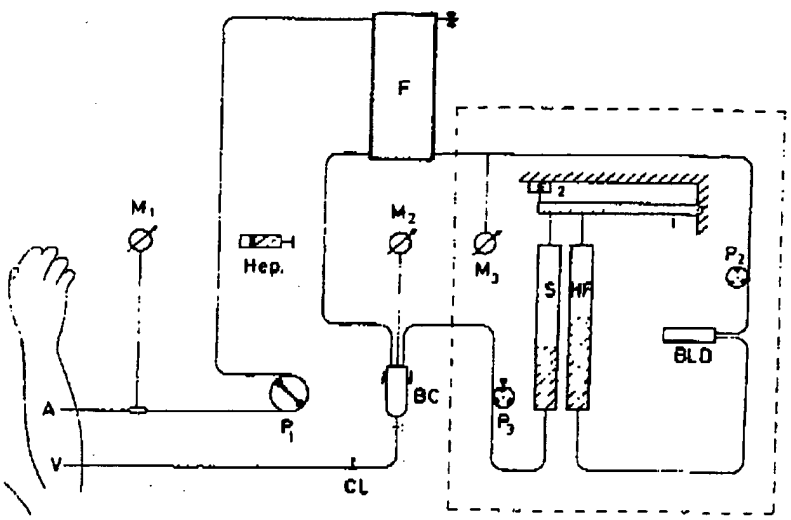
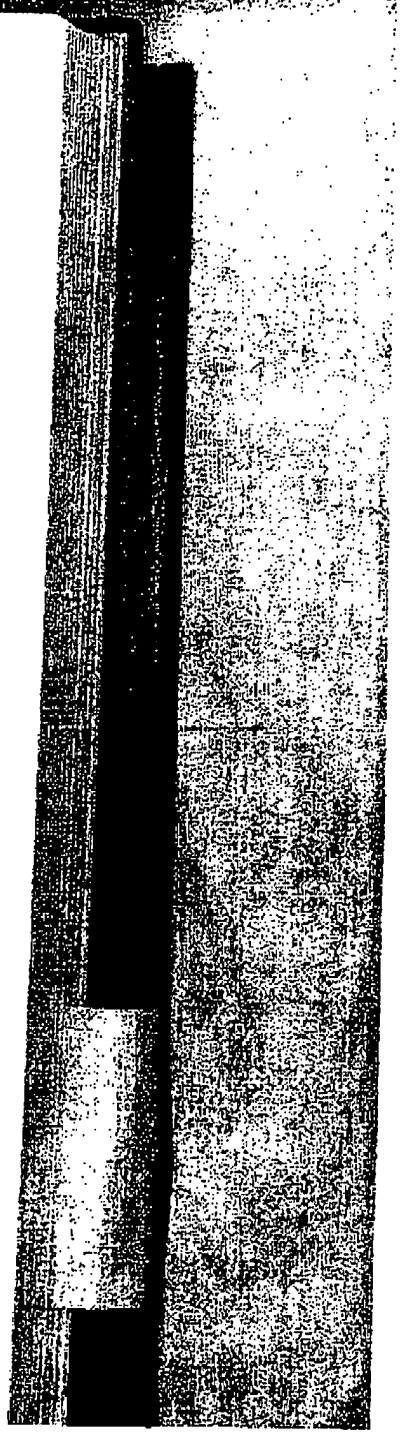



Fig. 5. Schematic diagram of first gravimetric hemofiltration system developed by DOHT, KLEIN, and QUELLHORST. Sustitution Fluid *(S)* and ultrafiltrate *(HF)* hang on a single scale with an electronic weight cell *(2)*. Proportional weight loss is programmed by the relative position of the ultrafiltration cannister *(HF)* on the lever *(1)*. (*F*, hemofilter: $P_1$, $P_2$, *P3*, pumps: $M_1$, $M_2$, pressure monitors; *BLD*, blood leak detector)

An attractively simple volumetric balancing system for slow arteriovenous hemofiltration was developed around 1978 by P. KRAMER at the University of Göttingen and manufactured by Schi-Wa Arzneimittelwerk, 4518 Bad Laer, West Germany [5] (Fig. 3). This weight-driven system operates entirely without pumps. It consists of a flexible bag for substitution fluid in a hermetically sealed box open only to the ultrafiltrate line. A weight pushes on this bag and forces substitution fluid out, thereby creating the negative pressure for ultrafiltration. As the substitution fluid bag empties, the box is gradually filled with ultrafiltrate. The apparatus contains also an electronically controlled valve, which bypasses the ultrafiltrate at timed intervals for programmable weight loss. Despite its simplicity, only a few units of this type have been built.

A unique volumetric hemofiltration machine was developed and manufactured by Nipro Medical Industries, Tokyo, Japan (Fig. 4). Volumetric control of balance in the Nipro NY-3 hemofiltration system is achieved by a roller pump with identical pump segments for ultrafiltrate and substitution fluid. A sophisticated circuit matches the positive pressures in the pump segments and prevents the interference of air with the volumetric control. Another unique feature of this machine is that it is designed to draw the substitution fluid from a large number of 1-liter glass bottles. This equipment has found only little use outside Japan.



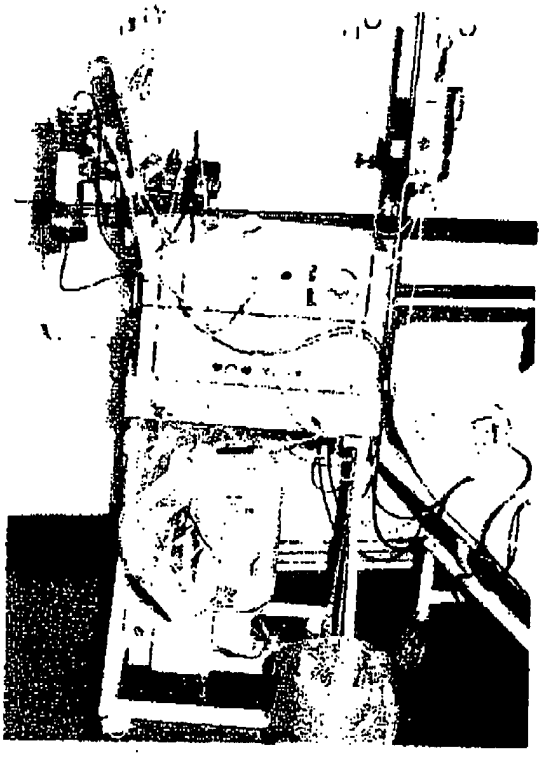


Fig. 6. Hemofiltration system BF 911 (Bellco-Deutschland GmbH, Freiburg, West Germany) in use at the Nephrologisches Zentrum Niedersachsen

## Gravimetric Systems

The first workable gravimetric system for hemofiltration was developed in 1976 by B. Dohr and E. Klein with E. Quellhorst in Hann. Münden, West Germany [6], (Figs. 5, 6). It was later manufactured as BF 910 and BF 911 by August Fischer KG in Göttingen, West Germany (now defunct), and distributed by Bellco-Deutschland GmbH, 7800 Freiburg, West Germany. The balancing system consists of a single scale with a transducer-type weight cell and operates by maintaining constant weight throughout the treatment. At the onset, the scale is electronically zeroed at the weight of the empty container for ultrafiltrate and the full one for substitution fluid. As ultrafiltrate is generated during the treatment, the weight on the scale increases. This in turn activates the substitution pump to draw substitution fluid from

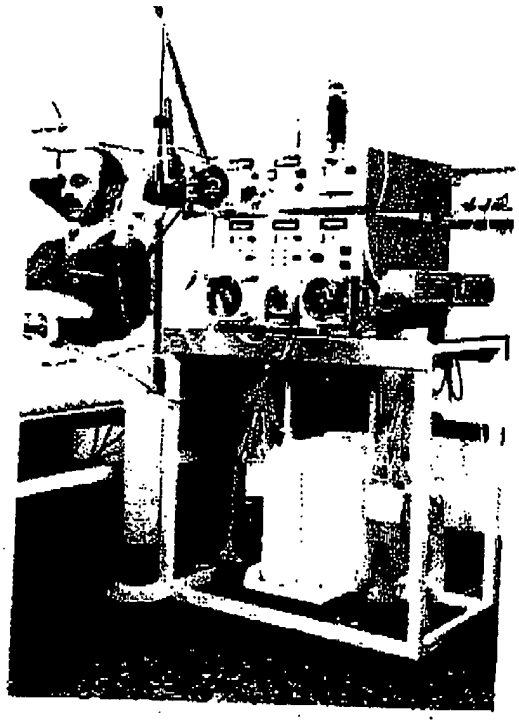


Fig. 7. Hemofiltration system AFG 02 (Dialyse Technik GmbH, Karlsruhe-Forchheim, West Germany)

the scale and deliver it to the patient. Programmable weight loss is achieved mechanically in a simple, imaginative fashion: The scale hangs on the weight cell by a lever, which articulates in a joint fixed to the frame of the machine. While the substitution fluid hangs directly under the weight cell, the cannister for the ultrafiltrate can be moved on this lever, thereby reducing the weight momentum sensed by the scale. Proportional gradual weight loss is achieved by this approach throughout the treatment. The maximal capacity for exchange, primarily dictated by the dimension of the ultrafiltrate container, was 20 liters for the model BF910 and was later increased to 30 liters for the BF911. These sturdy machines operate with good reliability and accuracy and have been in use in Hann. Münden, Hannover, Milan, and New York. A total of about 25 such machines have been built.

A similar gravimetric machine was developed around the same time at the Technische Hochschule Aachen, West Germany, and later manufactured as Hemofiltration System DT and AFG 02 by Dialyse Technik GmbH, 7512 Karlsruhe-Forchheim, West Germany. It uses the same single-scale approach for balancing control. It differs, however, in the way the programmed weight loss is achieved: A separate small pump removes ultrafiltrate at a preset rate from its circuit before it

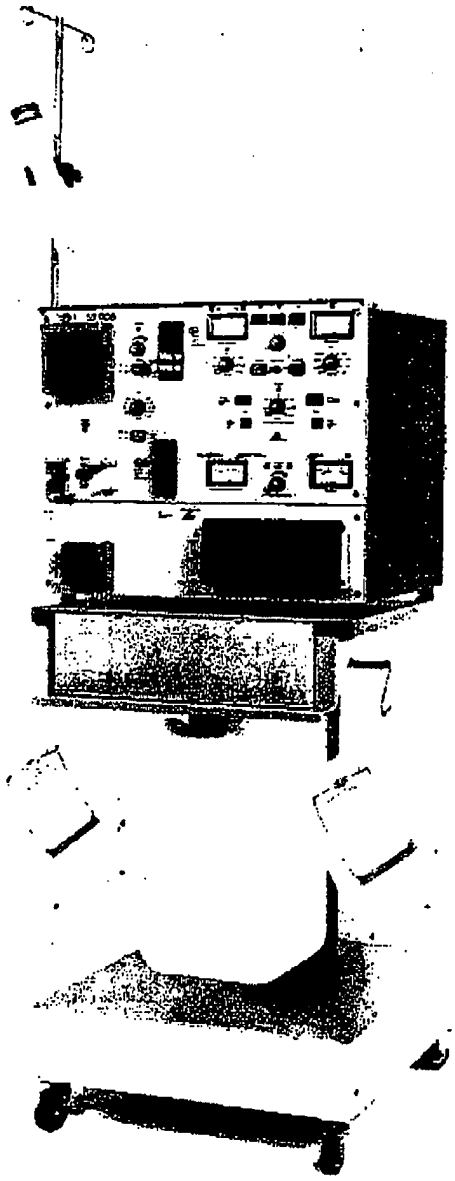


Fig. 8. Hemofiltration system SIF 905 (SIFRA, Società Italiana Farmaceutici Ravizza, Isola della Scala, Italy)

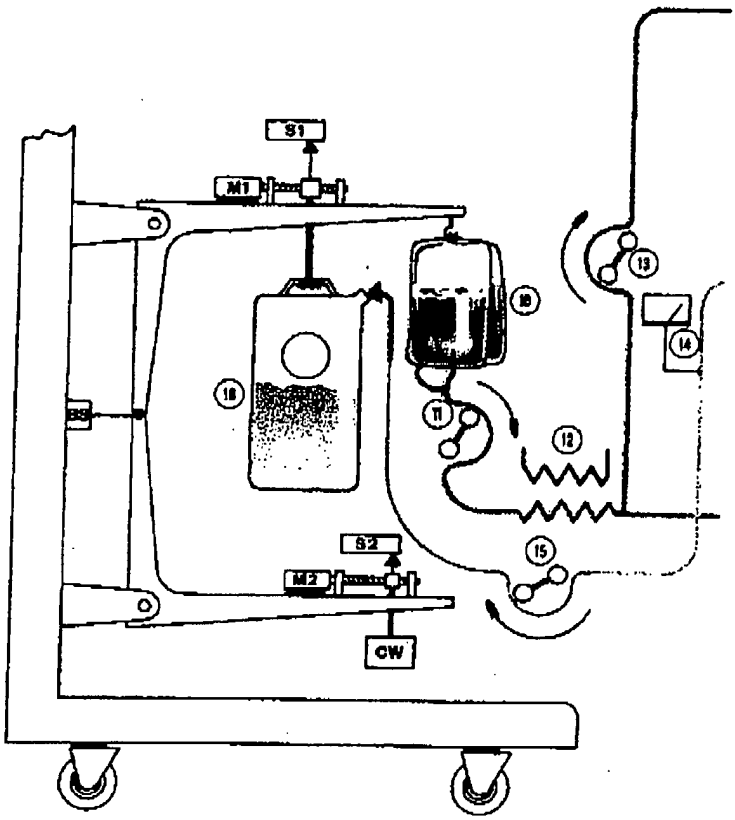



Fig. 9. Schematic diagram of the gravimetric control in the SIF 905 hemofiltration machine. Fluid balance is achieved by automated positioning of the ultrafiltrate cannister and a counterweight *(CW)* on a mechanical scale. (M = electric motors, s = sensors, BS = potentiometer controlling substitution pump, 10 = substitution fluid, 11 = substitution pump, 12 = heater, 13 = predilution pump, 14 = pressure monitor, 15 = ultrafiltrate pump, 16 = ultrafiltrate container)

reaches the container on the scale. While total volume of weight loss is conveniently collected in this approach, imbalance between ultrafiltration and substitution may be disproportionate towards the end of the treatment, when ultrafiltration rates are lower. The maximal capacity of exchange is 20 liters. The system is still manufactured and is used mainly in West Germany (Fig. 7). A newer model AFO 04 operates with two microprocessor-controlled scales and alleviates the above drawback.

A functionally entirely mechanical single-scale gravimetric hemofiltration machine was developed in 1979 by G. FRIGATO and B. VON ALBERTINI and manufactured as SIF 905 and SIF 907 by SIFRA, Isola della Scala (VR), Italy (Figs. 8, 9). In-

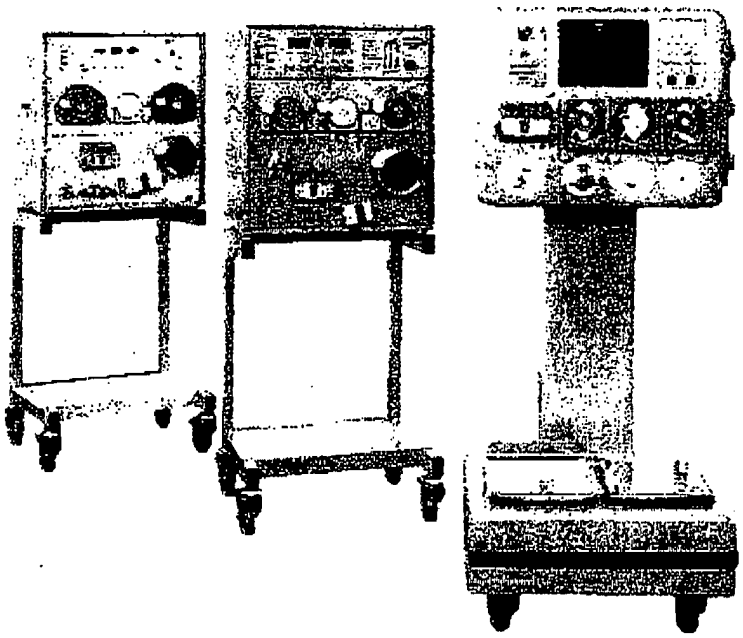


Fig. 10. Three generations of hemofiltration systems offered by Sartorius GmbH, Göttingen, West Germany. From *left*, Hemoprocessor HP40001, HP40005, HP40020

stead of an electronic weight cell, this system is based on a mechanical scale with adjustable counterweights. Operationally, it resembles the first of the aforementioned gravimetric systems. The position of the counterweight for zeroing the scale at the onset and the relative position of the ultrafiltrate container on the lever arm of the scale are achieved by electric motors, which at the same time provide the information for the electronic display of total exchange, weight loss, and substitution rates. In its operation, the rate of the substitution pump is determined by a simple potentiometer, which is activated by the tilting of the scale under the weight of the incoming ultrafiltrate. The mechanical functioning of this system prevents malfunctions and alleviates the complex circuits needed for the amplification and processing of electronic weight cells. Unique features of this system are the total exchange capacity of 36 liters and a predilution pump specifically designed for high-performance, combined pre- and postdilution. Close to 100 machines of this type have been built and are in use throughout Italy.

The first microprocessor-controlled hemofiltration system with two separate scales for ultrafiltrate and substitution fluid was developed in 1976 by a leading manufacturer of precision scales, Sartorius GmbH, 3400 Göttingen, West Germany.

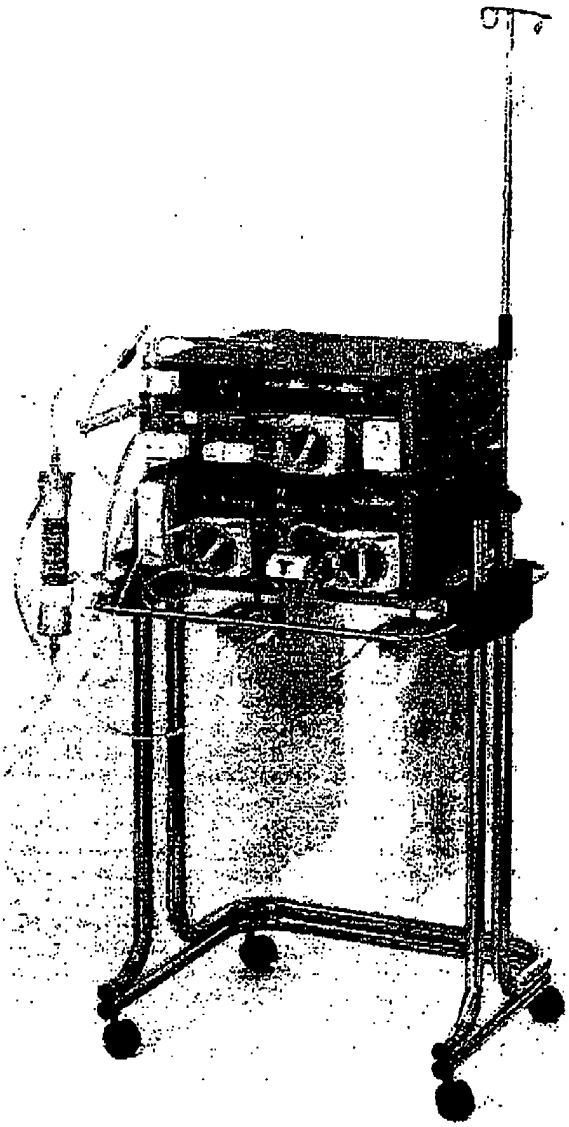


Fig. 11. Gambro (Lund, Sweden) system for hemofiltration, showing the blood monitor BMM 10-1, the hemofiltration monitor HFM 10-1, and the hemofilter FH 77

During hemofiltration

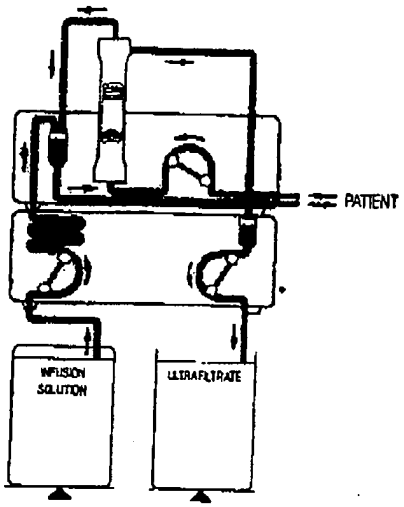



Fig. 12. Operating diagram of the Gambro hemofiltration system

under the leadership of E. KNOTHE and V. REICHE in close association with the nephrologists at the University of Göttingen. The Sartorius Hemoprocessor consists of two very precise electronic scales and operates under the control of a digital microprocessor (Fig. 10). Besides being fully programmable, this system provides continuous information about the rates of exchange during treatment, monitors all the safety features, pinpoints eventual malfunctions, and automatically primes the extracorporeal circuit at the onset of the treatment. It operates best with the flat-plate circular Sartorius hemofilters. Its advantages are its convenience and precision, as well as the elegant design. An initial disadvantage, the exchange capacity of only 15 liters, has been modified in the newest Hemoprocessor 400020, which can exchange 30 liters. In addition, the new model has a visual monitor displaying operational priming in all phases of the treatment. Several hundred of these systems have been built and are in use worldwide.

Starting in 1977, Gambro AB, Lund, Sweden, developed under the moving force of C. GULBERG and in consultation with K. SCHAEFER, Berlin, and S. SHALDON, Montpellier, an automatic hemofiltration system that became available around 1980 and is now in wide use as the Hemofiltration monitor HFM 10-1. The balancing system is modular and is used in combination with the blood monitor BMM 10-1. It consists of two separate, electronic weight cells for ultrafiltrate and substitution fluid and operates under the control of a microprocessor. Its total exchange capacity is 35 liters. The machine operates reliably and is not unduly complex to operate. Several hundred of these machines have been built and are used worldwide (Figs. 11, 12).

## Flow Control Systems

Experimental flotation-type and electromagnetic flow meters for monitoring fluid balance have been used clinically with predilution-hemofiltration, where ultrafiltration rates are relatively high and constant throughout the treatment [7]. A system operating with electromagnetic differential flow meters is under development by Gambro for a machine with in-line fluid production for hemofiltration.

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